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ADP013165

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9th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 18–22, 2001

NT.20p

Thickness-roughness phase diagram of multilayer ferromagnet-antiferromagnet nanostructures and their hysteresis loops

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Abstract. For a three-layer system consisting of two ferromagnetic layers separated by an antiferromagnetic interlayer it is shown that the stability region of single-domain ferromagnetic layers is technologically dependent on the ratio between the width of interface atomic steps and the thickness of layers. The thickness-roughness phase diagram has three regions: a collinear orientation of the magnetizations of ferromagnetic layers (1), oriented to each other at 90° (2), and a multidomain structure of ferromagnetic layers (3). The proposed approach can be compared with experiment by studying magnetic hysteresis loops against nanostructure layer thicknesses and their roughnesses owing to atomic steps on interfaces.

Introduction

The discovery of giant magnetoresistance [1] has stimulated interest in sandwiches consisting of alternating thin ferromagnetic (Fe, Co) and nonmagnetic (Cr, Cu) metallic layers.

An antiparallel or parallel orientation of adjacent ferromagnetic layer magnetization is energetically favorable when the number of atomic planes in the antiferromagnetic spacer is even or odd, as in Fig. 1(a) and 1(b) respectively. In the latter case an external magnetic field changes the antiparallel orientation of magnetization to parallel one. It is accompained by a drop in the electric resistance up to tens of percent.

An example of such a layered antiferromagnet is a chromium film with the thickness 32 Å $< d <$ 150 Å, in which at low temperature there appears a commensurate transverse spin-density wave [2]. A similar structure occurs when the iron impurities with the concentration exceeding 2% are introduced into chromium [3].

The roughness of the interfaces owing to atomic steps on them can make the uniform order parameter distribution energetically unfavourable, because the spin orientations of adjacent atoms on the step are opposite (Fig. 2). If the characteristic distance R between atomic steps exceeds some critical value, it is energetically favourable to break up the layers into domains with parallel and antiparallel orientation of magnetization [4].

In this paper we report a phase diagram of multilayer ferromagnet–antiferromagnet nanostructures with arbitrary ratios between the exchange interactions as well as between the layer thickness and the characteristic separation of steps at interfaces. The proposed approach can be used in the experiments studying the forms of magnetic hysteresis loops.

1. Description of the model

We shall investigate the disrtibution of order parameters in layers in the mean-field approximation [5, 6]. The parameters can be introduced for each layer as follows: the magnetization vector for ferromagnetic layers and the antiferromagnetism vector, equal the difference in

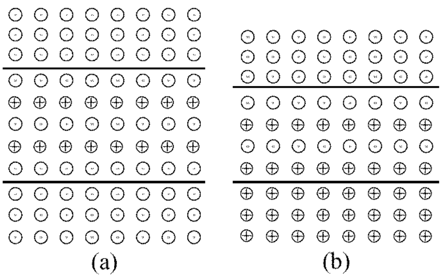

Fig. 1. Orientation of spins in a three-layer system consisting of two ferromagnetic layers and an antiferromagnetic interlayer in the case of smooth interfaces and odd (a) and even (b) number of atomic planes in the interlayer.

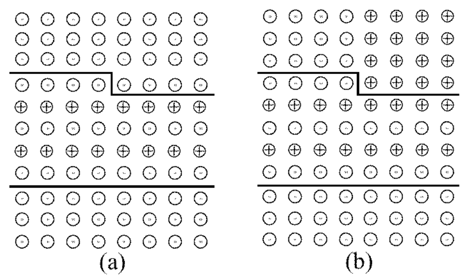

Fig. 2. Orientation of spins near the step at the interface for homogeneous distribution of the order parameters (a) and in the presence of a domain wall (b).

the magnetizations of sublattices, for antiferromagnetic layers. In case of sufficiently thin layers, the spins of atoms lie in the plane and, therefore, the orientation of the vector order parameter can be given by the angle θ that it forms with the x axis, which lies in the plane of the layer.

Far from Curie and Neel temperature, the exchange energy W_i caused by the interaction inside the ith layer can be written as

$$W_i = \frac{A_i}{2} \int (\nabla\theta_i)^2 \,\mathrm{d}V, \tag{1}$$

where the integral is taken over the volume of the layer, and A_i is the corresponding exchange constant. In the order of magnitude, $A_i \sim J_i S_i^2/b$, where J_i is the exchange integral between adjacent atoms, b is the interatomic distance, and S_i is a mean spin of an atom.

The energy of the exchange interaction between adjacent layers with numbers i and $i+1$ can be written

$$W_{i,i+1} = \pm B \int \cos(\theta_i - \theta_{i+1}) \mathrm{d}S, \tag{2}$$

where integration is performed over the layer interface, $B \sim J_{f,af} S_i S_{i+1}/b^2$, $J_{f,af}$ is the exchange integral between adjacent atoms belonging to different layers, and the sign " $+$ " is opposite for different sides of an atomic step at the interface of the layers.

We divide all distances by b, assuming it to be virtually identical in both sorts of layers and divide all energies by the constant A_{af} for an antiferromagnetic layer. We introduce dimensionless parameters

$$\alpha = \frac{J_{f,af} S_f}{J_{af} S_{af}} \text{ and } \gamma = \frac{J_f S_f^2}{J_{af} S_{af}^2}, \tag{3}$$

where the subscripts f and af correspond to a ferro- and antiferromagnet.

By varying the parameters θ_i in (1), we obtain a differential equation that describes the distribution of the order parameter in a layer

$$\Delta\theta_i = 0. \tag{4}$$

A more careful procedure is needed to obtain correct conditions at the interface of layers. The energies of intra- and interlayer interactions must be varied in a discrete model, and then we must go to a continuum limit. As a result we get

$$\widetilde{\Delta}\theta_i - \frac{\partial\theta_i}{\partial n} = \mp\frac{B}{A_i b}\sin(\theta_i - \theta_{i+1}), \tag{5}$$

where $\widetilde{\Delta}$ is a two-dimensional Laplacian in the plane of a layer, $\partial/\partial n$ is the derivative in the direction of an outer normal to the boundary of the layer, and upper and lower signs in (5) correspond to those in (2).

Thus, to find the distribution of order parameters in a multilayer nanostructure, it is necessary to solve the system of linear differential equations (4) with non-linear boundary conditions (5). The distribution will depend on the values of α and γ, on the thickness of layers, as well as on the characteristic distance R between the steps at the interface of layers.

2. Phase diagram of a three-layer system

The results of model calculations can be shortly displayed on the phase diagram (Fig. 3). Phase 1 is characterized by the presence of static vortices at the interfaces and a collinear orientation of magnetization of ferromagnetic layers. In phase 2, the magnetizations of the ferromagnetic layers are homogeneous and, in the absence of an external magnetic field, are oriented to each other at 90°. Phase 3 corresponds to a multidomain structure of ferromagnetic layers.

The phase diagram can be compared with experimental data by studying the state of ferromagnetic layers using a magnetic-force microscope with various ratios between R and a and different temperatures, because α and γ are temperature-dependent.

3. Effect of a magnetic field: hysteresis loops

The magnetic flux reversal of ferromagnetic layers in phase 1 occurs virtually independently, and the hysteresis loops must coincide with those in a two-layer system consisting of one ferromagnetic and one antiferromagnetic layer. Here and below we assume that the maximum magnetic field is much less than the exchange field in the antiferromagnet. Therefore, the magnetization of antiferromagnetic layers can be neglected.

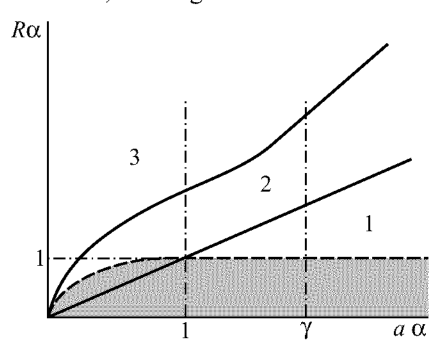

Fig. 3. Thickness-roughness phase diagram for a three-layer system consisting of layers of identical thickness. The region of weak distortion of order parameters is hatched.

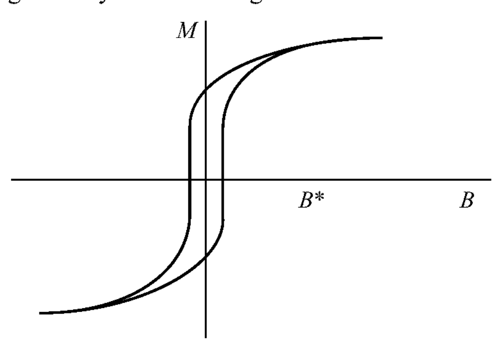

Fig. 4. Hysteresis loops of a three-layer nanostructure consisting of two ferromagnetic layers separated by an antiferromagnetic interlayer with identical thickness.

In phase 2, in a weak magnetic field that exceeds the anisotropy field in the plane of ferromagnetic layers, the magnetizations of ferromagnetic layers are oriented at 45° to the field while remaining virtually perpendicular to each other. In this case, the magnetization of the system is $M_{\max}/\sqrt{2}$, where $M_{\max}$ is the maximum magnetization of ferromagnetic layers. Its further evolution can be studied by minimizing the sum of the energies of ferromagnetic layer interaction with each other and with the magnetic field. The energy of a ferromagnetic layer in the magnetic field with inductance B is given by

$$W_f = -2\mu l B \cos \frac{\Psi}{2}, \tag{6}$$

where μ is the magnetic moment of an atom of a ferromagnet. For the angle Ψ between the magnetization of layers we have a transcendental equation

$$\frac{J_{af} S_{af}^2}{a} \left(\frac{\pi}{2} \Psi \right) = \mu l B \cos \frac{\Psi}{2}. \tag{7}$$

The characteristic field B^* (Fig. 4) at which there occurs a substantial magnetization change is

$$B^* \approx \frac{J_{af} S_{af}^2}{\mu a l}. \tag{8}$$

In phase 3, in a weak magnetic field, the domains with parallel orientation of the magnetization of layers are oriented along the field. In this case the system magnetization is $M_{max}/2$. The magnetizations of ferromagnetic layers in domains with antiparallel orientation in a zero field behave similarly to the magnetizations of the sublattices in the volume of an antiferromagnet. They are oriented virtually perpendicular to the external field.

As B increases, the angle Ψ between them decreases. The characteristic value of induction B^* of the external magnetic field in which the angle varies substantially, is found by the method similar to that for phase 2 and is given in order of magnitude by (8). Therefore, the form of the hysteresis loops in phases 2 and 3 differs only in the magnitude of magnetization in weak fields.

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